

SKIN-FRICTION MEASUREMENTS IN AN INCOMPRESSIBLE PRESSURE-GRADIENT TURBULENT BOUNDARY LAYER. REVIEW OF TECHNIQUES AND RESULTS

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1. Introduction

Experimental definition of the local and integral values of friction drag of an aircraft or its elements is one of the basic problems of applied aerodynamics. We also should note the undoubtedly significance of this value for the development of modern lifting profiles and other aircraft elements, the description of near-wall flows in a form of similarity laws and testing of the numerical techniques of computation of flow around such aircrafts. However, to define this value accurately, one should have a clear conception of the possibilities and efficiency of application of one or another technique for a special case of body flow around. Though any experimental work assumes application of a certain concrete technique, including one for skin friction finding, the available literature information is as a rule uncoordinated, i.e., this information reflects only the level of availability of the technique applied. For this reason the researches like [1, 2] devoted to the development of new techniques and investigation of the efficiency of the known ones under various experimental conditions, become very important.

The simplified layout (Fig. 1) gives a pictorial view of the main techniques of skin friction measurement, existing at the present time. The detailed consideration of these techniques is given in [3].

The present paper presents a comparative analysis of a number of direct and indirect measuring techniques when they are applied in an incompressible turbulent boundary layer of a flat plate under the conditions of formation of an unfavorable (positive) and favorable (negative) streamwise pressure gradients on the plate surface, and also in plate gradient-free flow around.

2. Experimental conditions and techniques

The experiments were carried out in a subsonic wind tunnel T-324 of the ITAM SB RAS at the velocity of an undisturbed flow in a reference cross section of $U_\infty = 24.9$ m/s (zero and positive pressure gradient) and of 20.3 m/s (negative pressure gradient), which corresponded with Reynolds numbers for 1 m of $Re_1 \approx 1.65 \cdot 10^6 \text{ m}^{-1}$ and $1.35 \cdot 10^6 \text{ m}^{-1}$.

The measurements were carried out on a flat plate model made of D16T alloy with the sizes of $2500 \times 993 \text{ m}^2$ in a plane and of 6 mm thick. The model was mounted horizontally in the test section of the wind tunnel on guiding rails. Both leading and trailing edges of the plate, as viewed from the non-operating side, are of semi-elliptical form with half-axes ratio of $b/a = 1:12$. The form of the proper leading edge is characterized by a radius rounding $r = 0.4$ mm. The centerline of the plate has a group of static pressure taps 0.4 mm in diameter). The scheme of the experiment, including model design, is given in [4].

Artificial tripping of the boundary layer was performed by coarse-grain sand paper 6 (with smoothed steps) of 15 mm length and 0.6 mm height which was glued over the plate span in the region of the maximum change in pressure observed in the vicinity of the leading edge.

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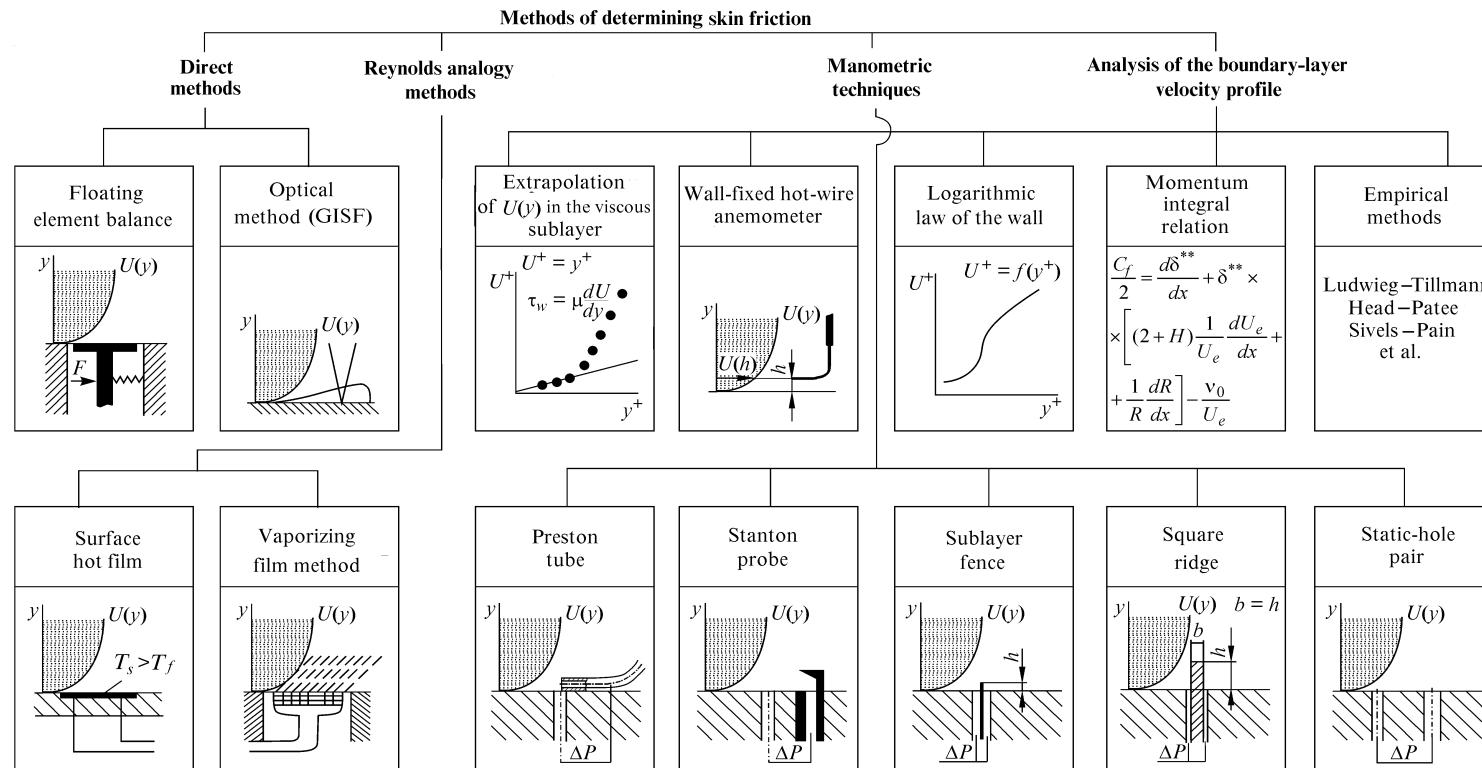


Fig. 1. Simplified classification of the main techniques for determining skin friction.

To generate a boundary-layer flow with a streamwise gradient, a special adjustable dummy wall 9 was used. It was made of a sheet of glass fibre laminate of 3.7 m length and 2.5 mm thick which was fastened to the wind-tunnel ceiling with cross-mounted guides allowing to vary a wall profile along the flow. During the experiments the dimensionless positive pressure gradient P^+ varied over the plate within the range of $(2.11 - 5.23) \cdot 10^{-3}$, where $P^+ = \nu(dP/dx)/\rho v_*^{-3}$. The negative pressure gradient varied within the range of $(1.88 - 3.17) \cdot 10^{-3}$.

To carry out the measurements in the boundary layer, a remote-control traversing gear 7 was used. Together with the standard traversing gear of the wind tunnel, it ensured an accuracy of ± 0.01 mm in the y direction and ± 0.5 mm in the x and z directions.

The mean velocity in the examined point of the flow field and the streamwise component of velocity fluctuations were measured by DANTEC hot-wire equipment. The primary transducer was a miniature hot-wire probe with a single straight sensor made as a tungsten wire 5 μm in diameter and 1.2 mm active long.

To determine local values of a skin friction coefficient a Preston method was applied. Depending on test conditions, three or two tubes were used; their outer diameters were 1.06, 1.61, and 2.01 mm, and the ratio of the inner to the outer diameter was 0.62. Computation of the skin friction coefficient C_f was carried out with the use of a modified Patel's calibration dependence as a averaged value from the results of measurement with several tubes.

3. Results of the experiments

3.1. Case of $dP/dx \approx 0$. The final experimental data of the wall shear stress distribution over the plate, which were obtained by several techniques, are presented in Fig. 2 as a dependence of $\tau_w = f(\bar{x})$. Symbols show the results of the experiments by Preston tubes, with a sublayer fence, an optical method of an oil drop, and a floating element balance; lines present the data determined on the base of analysis of the momentum integral equation and by Clauser approach. A vertical line shows the doubled rms error of shear stress $\pm 2\sigma_{\tau_w}$, determined by sevenfold measurements of this value by the optic method.

As is seen, here takes place a usual progress of the dependence $\tau_w = f(\bar{x})$ which is observed in similar situations with Re_x variation, namely, the smooth decrease of the skin friction over the model length. As for the peculiarities of the techniques under consideration, the following should be noted. The difference between the experimental values of τ_w obtained by the pointed techniques do not exceed 5 % in most cases, including the data obtained by the method of integral relations if

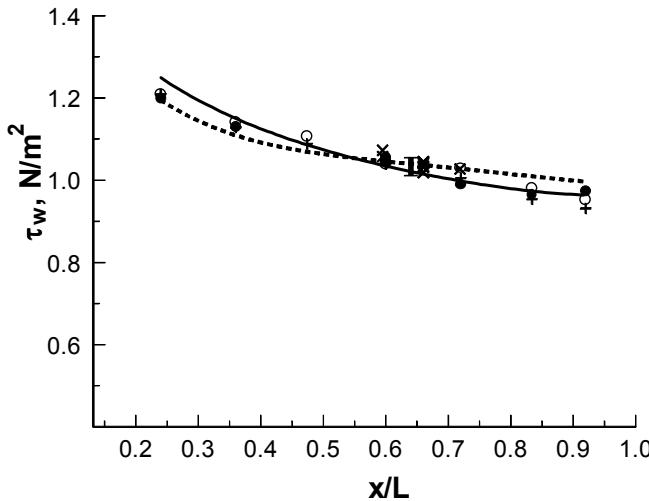


Fig. 2. Wall shear stress distribution of over the model at $dP/dx \approx 0$: o – Preston tube; • – sublayer fence; x – GISF; + – floating element; --- by Clauser method; — from momentum integral equation.

in the last case the procedure of differentiation of experimental dependence $\delta^{**}(x)$ is followed carefully. Thus, in general all the techniques applied in nominally gradient-free external flow should be considered as tantamount. The fact noted is not, however, so evident in the case of flow around the plate with the gradient external flow field being present.

3.2. Case of $dP/dx > 0$. The efficiency of the techniques used for this case could be inferred by the comparative analysis of the results obtained with these techniques presented in Fig. 3 as a dependence of $\tau_w = f(\bar{x})$ which gives the experimental data of wall shear stress distribution over the plate. Symbols show the results of the experiments by Preston method, with a sublayer fence, and an optic method of an oil drop; lines present the data calculated basing on Fernholz empiric formula [5]:

$$C_f = 0,058[\lg(8,05/H^{1,818})]^{1,705} \cdot Re_{\delta}^{-0,268}. \quad (1)$$

A vertical line shows a doubled rms error of $\pm 2\sigma_{\tau_w}$, determined from multiple measurements of the value of τ_w by the optic method.

It may be noted that the more considerable, as compared to the case of $dP/dx \approx 0$, decrease of the skin friction over the model length, which is normal under the action of the adverse streamwise pressure gradient. As for the peculiarities of the techniques compared, the following fact attracts attention. As evident, the results obtained by practically all measuring techniques correlate satisfactory to each other. The difference between the experimental values of τ_w obtained by the different techniques does not exceed approximately 5 % in most points. Thus, from this viewpoint these techniques should be considered as tantamount. This conclusion, however, is valid with one stipulation, namely, that the calibration of the indirect techniques is carried out in the conditions appearing right in the experiment. It is true, in particular, for the sublayer fence which calibration was carried out just at the gradient flow around the flat plate.

In principle, empiric formula (1) also follows approximately the behavior of dependence $\tau_w = f(\bar{x})$ under these conditions, but deviation of τ_w from the experimental values obtained by the main group of the techniques is much greater than the measurement error of this quantity. As for the method of integral relations, even the careful procedure of differentiation does not ensure an accuracy better than 15 – 18 %.

3.3. Case of $dP/dx < 0$. The experimental data of wall shear stress distribution over the plate for the case under consideration are presented in Fig. 4 as a dependence $\tau_w = f(\bar{x})$. Symbols show the results of the experiments by Preston method, with a sublayer fence, by an optical method of an oil drop (GISF), and by a floating element. As before ($dP/dx \approx 0$), the readings of Preston tube were used as a calibration dependence for τ_w definition by the sublayer fence. The quantitative data characterizing the error of the analyzed quantity were obtained on the base of multiple measurements of the shear stress by optical method and

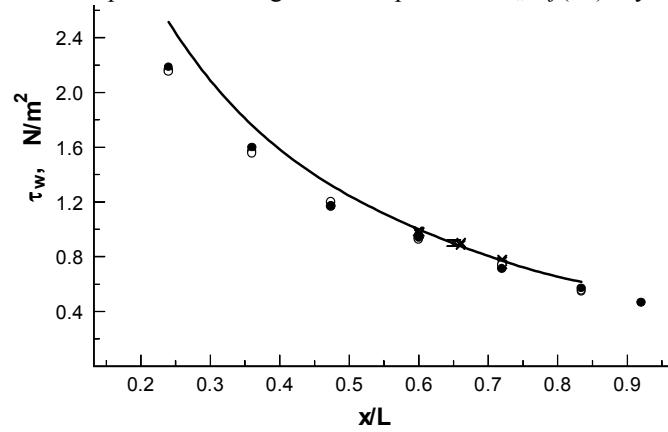


Fig. 3. Wall shear stress distribution over the model at $dP/dx > 0$:
 ○ – Preston tube; ● – sublayer fence; × – GISF; — by formula (1).

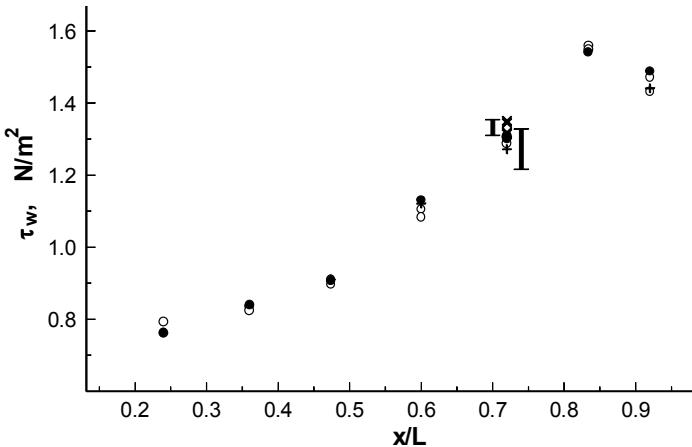


Fig. 4. Change of shear stress over the model at $dP/dx < 0$:
 o – Preston tube; • – sublayer fence; \times – GISF; + – floating element.

should be noted. At first glance it would seem that in this case also all analyzed experimental techniques may be successfully applied for skin friction measurement. Really in most points the difference between experimental values of τ_w deducted from these methods, does not exceed 5 – 7 %. Hence it follows with a certain probability that the measuring techniques applied under such conditions are approximately tantamount. But it is true in the case when the calibration of the indirect methods of measurement is carried out in conditions appearing right in the experiment. Besides, particular emphasis is placed upon greater scatter of the values of τ_w deducted with the aid of a floating element (a right vertical line). That means that this device cannot be used as a perfect method for flows with strong pressure gradients. It is established that this fact is appreciably connected to zero drift caused by variation of the temperature of semi-conductor strain gages before and after the experiments. It is clear that effective application (even) of relatively small-scale floating element of this type in the flows with strong pressure gradients is not so evident, and the device itself calls for further improvement.

Empiric formula (1) just roughly reflects the true behavior of dependence $\tau_w = f(\bar{x})$ under these conditions (not shown). The deviation of τ_w , calculated on the basis of (1) from the experimental results obtained by the basic methods, reaches the value of about 20 % in the last measurement cross section. A similar conclusion may be done for the application of momentum integral equation since in this case the error of τ_w definition increases still more. The major source of errors here lies in the fact that two terms in the right part of the equation have different signs, therefore the skin friction coefficient presents a small difference of the two great values.

4. Conclusion

(i) The results obtained demonstrate that the main methods being considered such as a floating element, optical (GISF), Preston tube, and a sublayer fence are roughly equivalent and may be successfully used under the mentioned conditions. At the same time, taking into account a number of advantages, in particular, the independence on flow state near the wall, absence in calibration demand, and possibility of panoramic measurements, the GISF-method presents the best instrument for such experiments.

with the aid of a floating element. The doubled magnitude of this value of $\pm 2\sigma_{\tau_w}$ is depicted with (the) vertical lines on the right and left from the corresponding averaged values.

As is seen, contrary to the case of $dP/dx > 0$, here the considerable increase of the shear stress is observed over the model length, which contain nothing unusual under the influence of favorable streamwise pressure gradient. As to the peculiarities of the methods being compared, the following

(ii) The behavior of Preston tube in the gradient flows being not completely understood, exclusive simplicity and high reliability of this techniques is confirmed. However, due to the effect of Preston tube on the readings of the static pressure tap nearby the tube, the direct registration of the pressure difference ($P_0 - P_i$) proportional to the shear stress, is impossible. The floating element, even with a relatively small balance face, may not be considered as a faultless method in the flows with strong pressure gradients.

(iii) Calibration of the indirect measuring techniques, including the sublayer fence method, should be carried out in the conditions appearing right in the experiment. With calibration dependence under canonic conditions, the results of the measurements may be incorrect.

(iv) The empiric formulas based on in an approximated dependence between a friction drag coefficient and the integral characteristics of the turbulent boundary layer, may not be used successfully for the mentioned purpose, except the cases of gradient-free or weakly gradient flows.

(v) The results obtained confirm that the method of integral relations may be applied for skin friction determination in a weakly-gradient shear flow only when an careful procedure (of differentiation) of experimental dependence $\delta^{**}(x)$ is followed. The effectiveness of this approach in a strongly gradient flow is questionable.

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